Air Temperature in summer on and around the Lake Inawashiro, Fukushima Prefecture

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Introduction

A matter of prime interest to the climatologists, especially to those who are interested in local climate, is the thermal influence of the earth's surface upon the air over it[1]. Many studies have been made on the thermal effects of the surface upon air temperature,– for example, the surface of the urban area[2], the sea,[3)4)] the cold water-mass[5] or the sea-ice[6]. On the other hand, its heat-modification of the air temperature by land has been examined[7)-11)] in the study of the sea-breeze.

It will be an adequate measure to estimate the modification of the air over the cold surface, in order to clarify the thermal effects of a lake, because it is

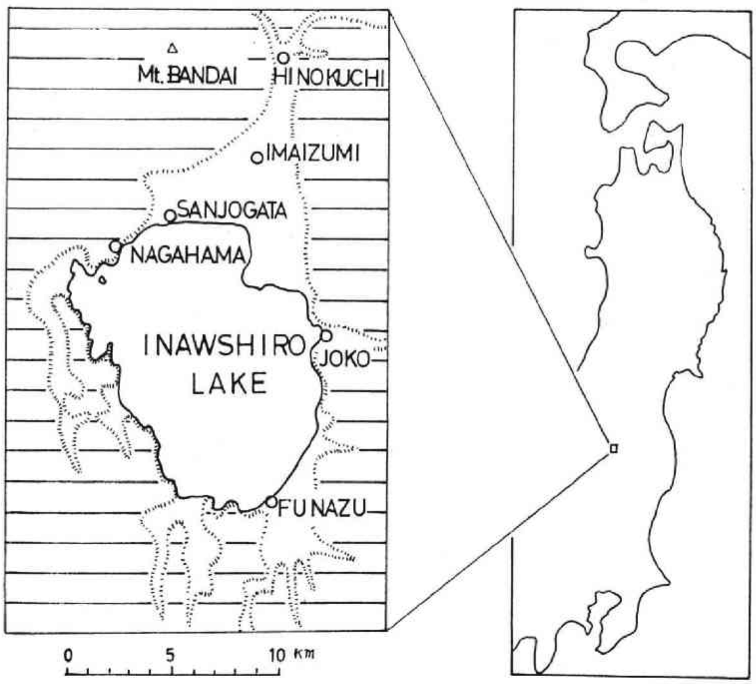

Fig. 1 Index map

surrounded by heat-soruce areas in the daytime in summer. In this paper, in such a view-point, the air temperature on and around the lake Inawashiro, Fukushima prefecture is described. The description is based mainly on the author's observations of temperatures made at five places around and near the lake during July 6th to 10th, 1963, and on the lake on July 7th (1963), 6th (1964) and 7th (1965).

1. Cooling of the air on the lake caused by the water surface

A) Diurnal variations of air temperature on windward and leeward shores of the lake

Fukui suggested[12] that in summer the surface had a cooling influence on the lake shore throughout a fine day in July. In order to analyze the cooling influence, it is effective to compare the air temperatures on windward and leeward shores, because the former is subject to the influence of the land air, while the latter to that of the lake air. Examples of temperature comparison between the windward and leeward shroes are shown in Fig. 2, when the northerly wind prevailed. On the

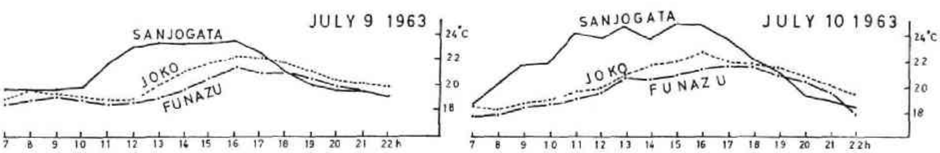

Fig. 2 Air temperature comparison between windward and leeward shores (Sanjogata: north-shore, Joko: east-shore, Funazu: south-shore)

windward shore (Sanjogata) free from the influence of the lake, air temperature rose quickly after dawn, while the rise was very slow on the south shore (Funazu) or on the east shore (Joko) when it blew from the lake. As in the latter places the maxima appeared much later, and the temperature difference far larger than the maximum temperature difference between the windward and the leeward shores lasted from morning till afternoon.

The air temperature at Sanjogata is compared with that of Funazu. The comparison is made concerning the daytime hourly data 09:00∼17:00, July 9th and 10th. The example shown in Fig. 3-I indicates a case of the north wind and Fig. 3-II, that of the southerly wind. Those examples show that the leeward shore is cooler than the windward shore under any flow-pattern over the lake. Magnitudes of the difference between both shores are mostly less than 2.8°∼4.5°C, in the case of the north wind (I in Fig. 3). Thus, it is obvious that the daytime air temperature on the lake shore is controlled by the wind direction, and that

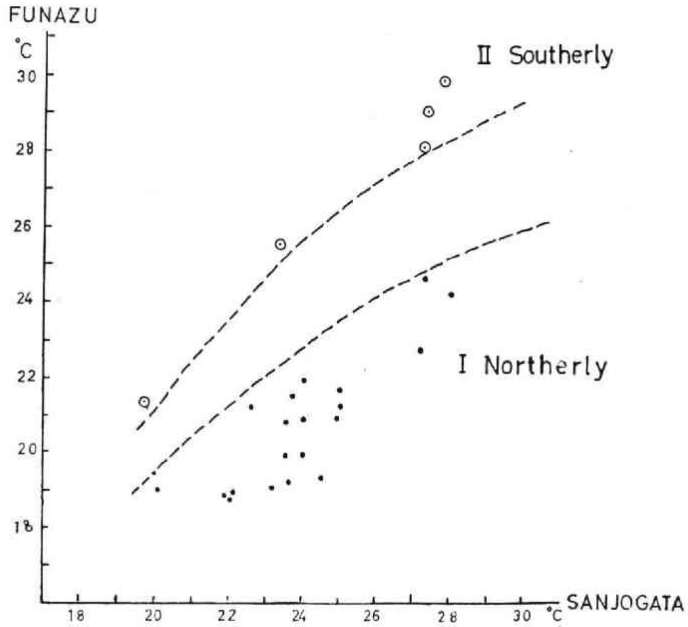

Fig. 3 Air temperature relation between windward and leeward shores
I: in the case of north wind II: in the case of south wind.

the flow-pattern over the lake plays an important role in the temperature relation between both shores.

B) Profiles of air temperature on the lake

Cooled by the lake surface, the air temperature ought to go down in accordance with the distance from the windward shore. An observation of the distribution of the air temperature on the lake, therefore, will be useful to understand the cooling

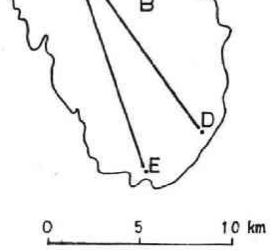

Fig. 4 Route map of air temperature observation

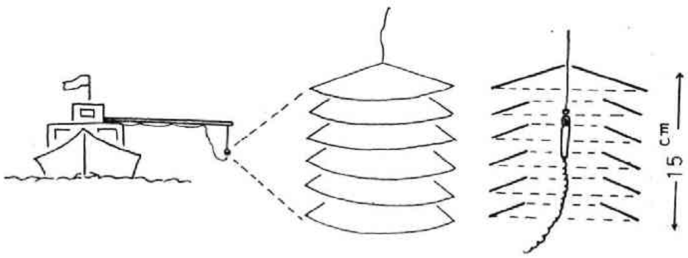

Fig. 5 Thermistor thermometer and its sun-shelter

effect of the lake surface. In this sense, the author made the air temperature observation using a boat along several routes (see Fig. 4) which were selected not only for the purpose of temperature observations but also for the sounding of the lake bottom topography.

Under a calm weather When the air pressure gradient is gentle on synoptic scale, calm conditions in this region are expected in summer not on a clear day when the lake breeze develops, but on an overcast day. It was under such weather conditions that the observation on July 7th, 1965 was made along Route A-D (for route see Fig. 4). The temperature on the lake was homogeneous in a large area excepting a narrow belt along the shore (Fig. 6).

Under northwesterly air-flow It was fine in the morning on July 6th, and the northwesterly wind prevailed. Along the Route B-A (Fig. 7-I, for route see Fig. 4) the temperature went down according to the distance from the windward shore, and this tendency was strengthened in the afternoon (Fig. 7-II) when the northwesterly wind blew more strongly. Fig 7-III shows the case where along Route A-B the air temprature temporarily rose when it was calm before the northwesterly wind started to blow again.

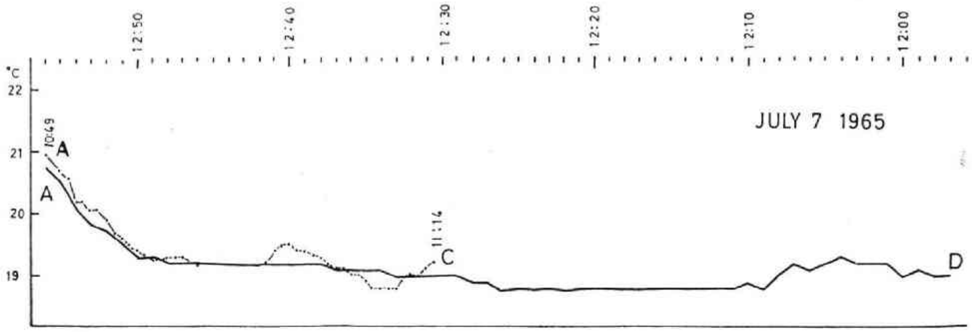

Fig. 6 Air temperature profile along the Route A-D under the condition of calm and cloudy weather

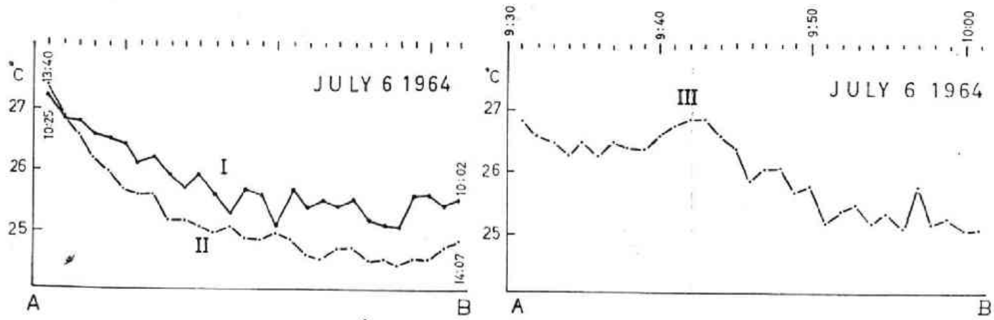

Fig. 7 Air temperature profile along the Route A-B under the condition of northwesterly wind
I: weaker wind II: stronger wind III: temporarily calm on the way

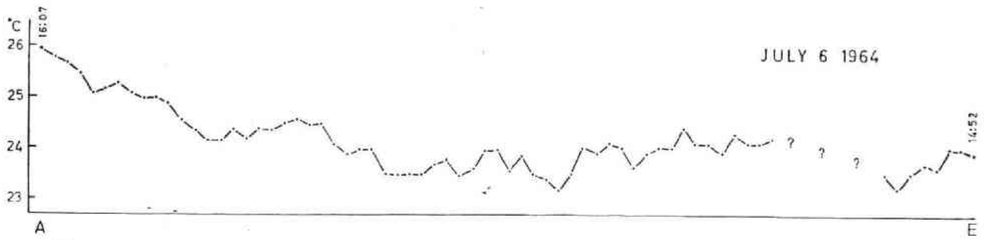

Fig. 8 Air temperature profile along the Route E-A under the condition of stormy weather

Under a stormy weather During the observations on July 6th, there was a change of the weather in the afternoon at about 14: 00 when it became stormy. Fig. 8 shows the air temperature along Route E-A in that weather. In spite of strong turbulence, there still was some temperature difference between the shore and the lake center.

From the facts mentioned above, the following inferences will be drawn.

i) The cooling of air on the lake becomes more effective when the air moves than when the air is stagnant.

ii) The drop-rate of the air temperature according to the distance from the shore is also affected by wind force.

iii) Even when the temperature difference between land and water is not so large, the cooling effect of water surface is expected to some degree under windy conditions.

These influences necessarily lead to the view-point that the problem of air cooling must be raised as to not only coldness of the water surface but also the loss of latent-heat due to evaporation caused by the wind. That view-point induces

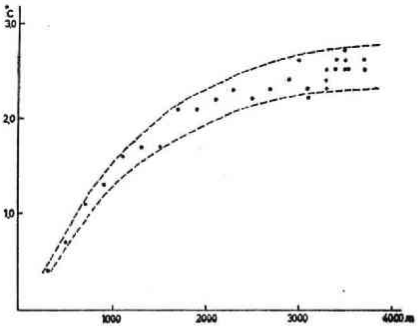

Fig. 9 Relation between air-flow distance on the lake and the reducing of air temperature under the condition of stronger wind

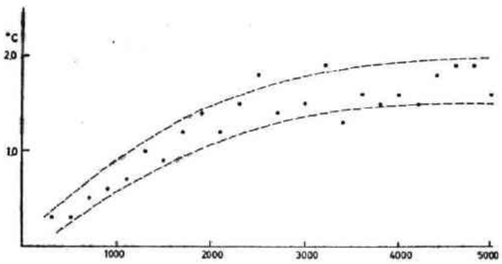

Fig. 10

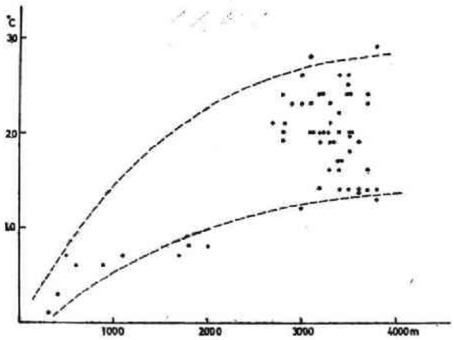

Fig. 11

Fig. 10 Relation between air-flow distance on the lake and the reducing of air temperature under the condition of weaker wind

Fig. 11 Relation between air-flow distance on the lake and reducing of air temperature under the condition of stormy weather

the author to expect the possibility of estimating the amount of evaporation from the lake surface based on the air temperature data around the lake.

C) Relation between air temperature and air-flow distance on the lake

The difference between the air temperature on the lake and that on the shore can be obtained along the observation routes. Regarding to the observation along Route A-B (quoted in Fig. 7-II), the NNW wind was blowing at first, but the wind direction changed to NW and then to N when the boat passed B. Along the route the distance from the windward shore to the boat location was measured as the range of the wind over the lake. The relation between the temperature difference and the distance thus measured or the air-flow distance over the lake, is given in Fig. 9, which shows the change of the difference with the distance. Inferring from the graph, the relation is not a linear one, but the rate of the change (per unit distance) is reduced rapidly with the increase of the distance. It is probably because the cooling effect of water upon the air will approach Zero when the air and the water attain to a heat-balance.

By the same method, Fig. 10 and Fig. 11 were obtained, the former referred to the data of Fig. 7-I and the latter to that of Fig. 7-III. In the graphs in these figures it seems to be common in the tendency that cooling effect varies with the air-flow distance.

Now, on a logarithmic graph (Fig. 12), the relation between x^2 (x is the distance from the windward shore) and T_d (air temperature difference from the windward shore) referred to the data of Fig. 9 may be expressed by two

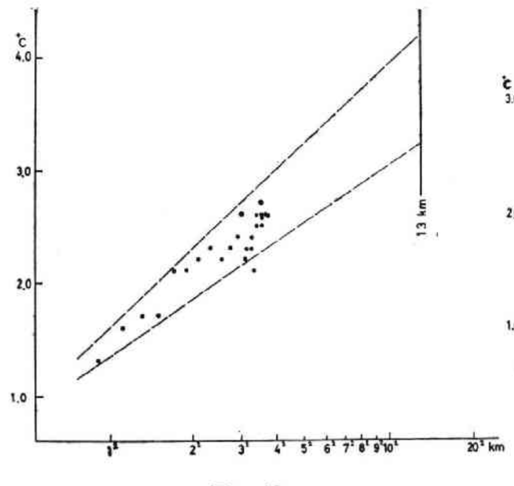

Fig. 12

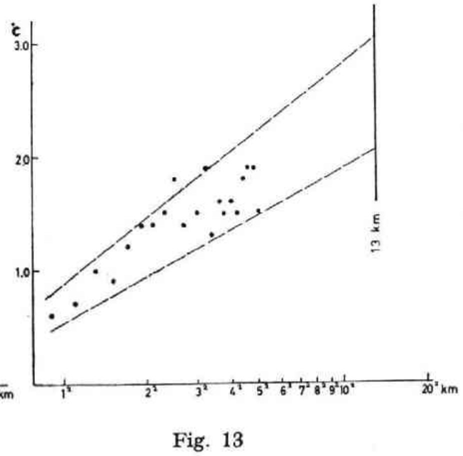

Fig. 13

Fig. 12 Relation on logarithmic graph between reducing of air temperature and square of air-flow distance on the lake based on the data of Fig. 9

Fig. 13 Relation on logarithmic graph between reducing of air temperature and square of air-flow distance on the lake, based on the data of Fig. 10

straight lines, the upper limit and lower limit, where $x > 1.0$ km. Referred to the data of Fig. 10, the relation shown in Fig. 13 can be obtained. Hence, the relation between x (< 1.0 km) and T_d is given by

$$T_d = a \log x^2 + b$$

where a or b, refers to wind and other weather conditions. Accordingly, air temperature, y, at any location on the lake is estimated by

$$y = A - a \log x^2 - b$$

where A is the air temperature on the windward shore.

D) Temperature difference between both shores of the lake

By means of the graph in Fig. 12 mentioned obove, the air temperature difference between the windward and leeward can be estimated when the distance between both shores is given. The temperature differences, when the north wind prevails, will be evaluated in the interval of 3.3°~4.2°C where that distance x is 13 km from north shore to south shore. Adopting such a method, the magnitude is read by 3.0°~3.9°C when the northwesterly wind prevails, because the distance of the lake surface is measured as 9km in this direction. The temperature differences thus estimated between the north shore and the south shore are given in the accompanying table. These magnitudes do not differ greatly form the above-mentioned data obtained from the real observations.

Table Estimation of air temperature difierences between windward and leeward shores

wind velocity / wind direction	4~6 m/sec	6~8 m/sec
N~NNW	2.1~3.1°C	3.3~4.2°C
NW	1.9~2.8°C	3.0~3.9°C

2. Air temperature on and around the lake when the lake breeze develops

A) A high temperature area over the lake center when the lake breeze develops

Mukade[13] reported in his study that in summer lake-and land-breeze well develop. July 7th, 1963 was a bright and clear day, and the lake breeze developed in the morning. The air temperature was observed on a boat along the route between the location A on the northwest shore (Nagahama) and the location I, the center of the lake. On the way to the center the thermometer was read every minute on the boat sailing on the lake, and on the way back, the temperature was measured at five location (I,H,G,F and A) holding the boat.

The air temperature profile along the route obtained in both ways are in Fig. 14. A warmer area was found over the central area, where it is calm, not a breeze

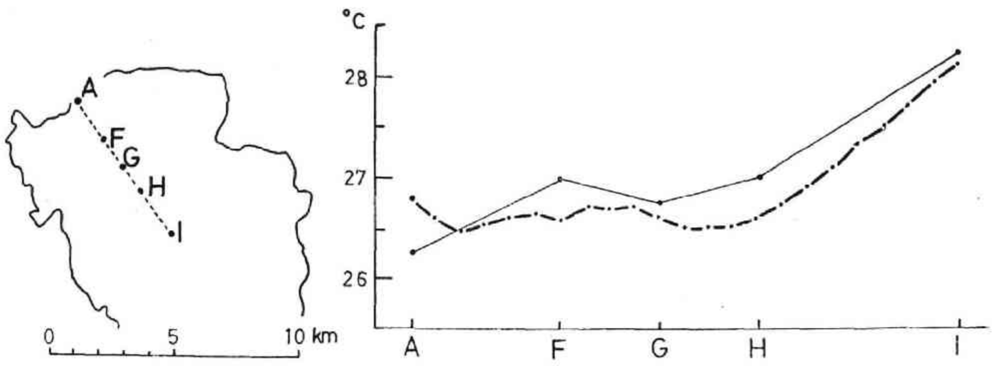

Fig. 14 Air temperature profile along the Route I-A when the lake breeze develops

stirred the lake, and the water surface was like a mirror. At that time, however, it breezed on the shores around the lake. It is supposed that a micro-anticyclonic circulation diverging from the center of the lake developed over the lake. This higher temperature over the lake will be explained as follows:

i) The drop of air temperature with the distance from the lake center twoard the shore may be due to the cooling effect of the water surface. When the lake breeze develops, the air flows on the water surface from off-shore toward inshore. Therefore a low temperature area due to the cooling of the water surface ought to develop inshore along a belt around the lake, and accordingly, the central part of the lake may be left as a relatively warm area.

ii) The lake center is regarded, at the same time, as the center of an anticyclonic wind-system, in which the air will be supplied to replace the diverging air with the air from the upper level, free from the cooling by the water surface. From such an influence the area, where the descending air current develops, will be expected not only over the lake center but also over the area with the secondary maximum in temperature shown in Fig. 14 as G-F.

B) Development of lake breeze and diurnal variation of air temperature on shores

The example quoted in Fig. 15 shows the air temperature variation on the lake shores when the lake breeze develops for a few hours. In the whole daytime excepting the hours, the SE wind prevails. And the south or the east shore experiences two kinds of wind; lake breeze from the water surface and the SE wind from the land surface. When the lake breeze begins to blow, there is a sudden drop in temperature on the south or the east shore, while, such a drop cannot be seen on the north shore on which the prevailing SE wind blows from the lake side just in the same direction as the lake breeze.

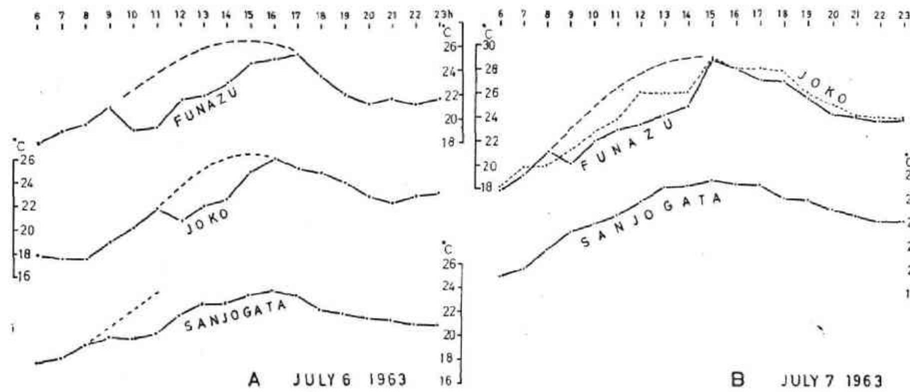

Fig. 15 Diurnal variation of air temperature on shores when the lake breeze develops

Fig. 15-B shows another diurnal variation on a clear day when the lake breeze developed in the morning. Influenced by the lake air in the morning, the temperature went up everywhere very slowly. At two places, the south shore and the east shore, continuance of the slow rise of temperature was checked by a sudden rise at about 14:00 when the southerly wind from the land side began to alternate with the lake breeze. On the other hand, the north shore experienced no radical change in temperature influenced by the lake air for a whole day. Hence, it can be explained that the sudden rise of temperature on the shore is due to the shifting of the air. Similar examples were seen on other days.

From these examples, one can conclude that when the lake breeze develops the differences of the air temperature around the lake are deduced.

3. Air temperature in the plain along the lake shore

The air temperature in the daytime (July 6th-10th) was observed at three locations in the plain along the north shore: Imaizumi, 3.5 km from the shore, Hinokuchi, 8.0 km from the shore and Sanjogata on the shore.

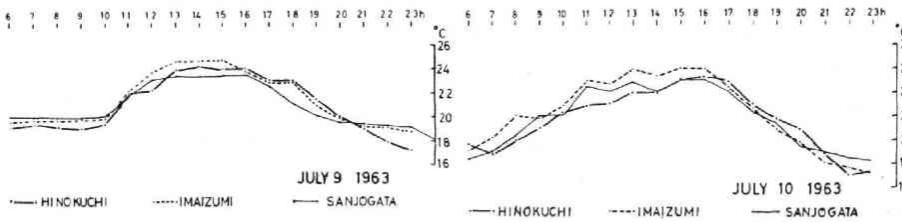

Fig. 16 Diurnal variation of air temperature at the places in the plain along the north shore

A) Diurnal variation in the air temperature and the air-flow pattern

Fig. 16 shows the examples of the diurnal variation of the air temperature when the N-NW wind prevails for a whole day. The air temperature at the three places in the plain is approximately same under the influence of air-flow from the land-side.

Another exmaple of the diurnal variation of the air temperature is shown in Fig. 17. The increase in temperature was slow on the shore and quick at interior places in the morning when the SE wind prevailed over the plain. The latter places continued to be warmed until the increase of temperature was checked by the appearance of the S wind at about 12: 00 at Imaizumi, and at about 13: 00 at Hinokuchi fartherst from the lake.

An example when the lake breeze develops over the plain in the morning, is

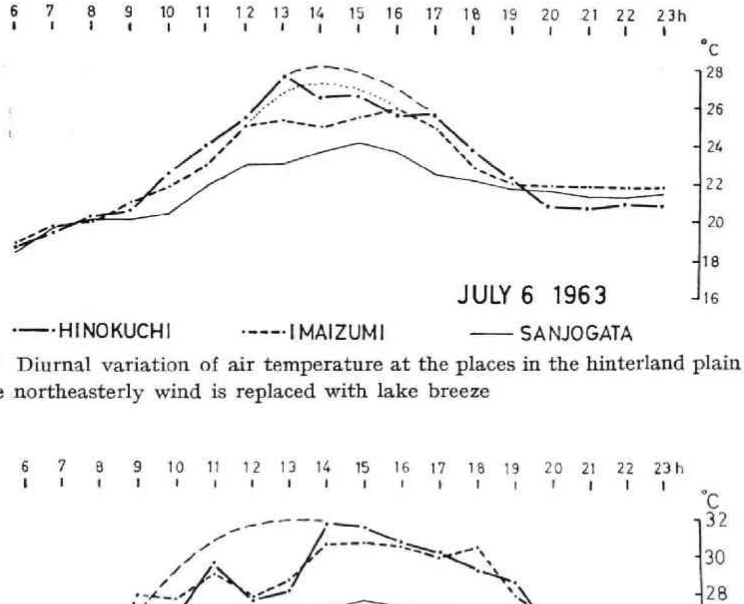

Fig. 17 Diurnal variation of air temperature at the places in the hinterland plain in the case northeasterly wind is replaced with lake breeze

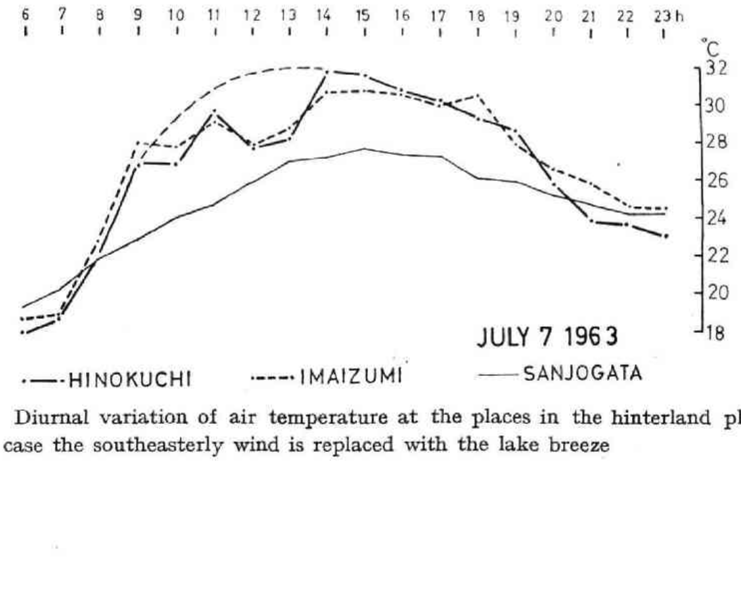

Fig. 18 Diurnal variation of air temperature at the places in the hinterland plain in the case the southeasterly wind is replaced with the lake breeze

shown in Fig. 18. When the lake breeze (S wind) develops, the air temperature can not rise fully until the late morning, but in the afternoon it becomes high at the interior places (Imaizumi and Hinokuchi) under the influence of the SE wind, while lower temperature continues in the daytime on the shore under either the S or SE wind. Therefore, air temperature difference between the shore and the interior place is larger under the SE wind than under the S wind. It is known that both the interior place Hinokuchi and Imaizumi scarcely differ each other in temperature under the latter wind.

Anyway, the characteristics of air temperature distribution over the plain along the lake are formed according to the pattern of air-flow.

B) Air temperature difference between the shore and the interior place

Concerning the hourly air temperature, magnitude relation between two places Sanjogata (on the shore) and Hinokuchi (farthest from the lake) can be compared each other in the graph in Fig. 19 according to the air-flow pattern over the region. The air temperature differences between these two places are in the interval $0° \pm 1.0°C$ when both places are free from the influence of the lake, and in the interval $2.5 \pm 0.3°C$ when they are under the influence. The difference is

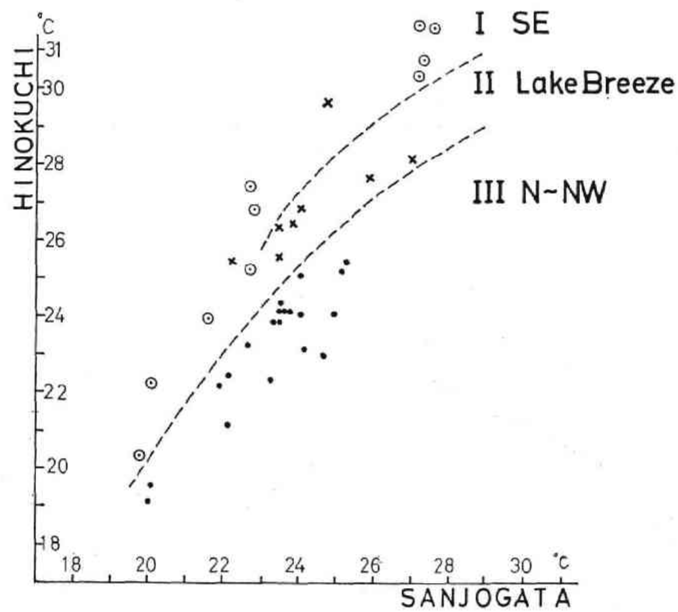

Fig. 19 Air temperature comparison lake shore with interior place of hinterand according to flow-pattern

largest when the shore is under that influence while the interior place is not.

From the graph in Fig. 18, it will be said that the air temperature at interior two places, Hinokuchi and Imaizumi, are nearly the same under the lake-breeze. In fact, the temperature of the two places begins to approach each other when the places experience the lake breeze as shown in Fig. 17. Such approximation of temperature values of the two places (Hinokuchi is 8.0 km, Imaizumi 3.5 km from the lake) suggests that the heat modification of the lake-breeze is limited to the shore area within 3.5 km from the lake.

Here, magnitude "2.5°C/≦3.5 km" is given as the air temperature gradient in this shore region. This magnitude, however, is much larger than the data obtained by former studies[7)-11)] on the sea coast. It is probably because the air layer of the lake breeze in this case is much thinner than that of the sea breeze, and accordingly because the modification of this layer may be completed easily within the area not so far from the shore.

C) Assumption of a lake breeze front

From what was mentioned above, it will be explained that the interior two places Hinokuchi and Imaizumi had an approximinately same condition concerning the air temperature because both were under the same system of air-flow. Considered from the view-point, each of the two places, showing fairly different temperature value at about 13: 00 as shown in Fig. 17, must have belonged to the different system of the air. That is, while the SE wind was still blowing at 13: 00 over Hinokuchi, the lake breeze must have already begun to blow over Imaizumi. This necessarily leads to the assumption of the existence of a lake-breeze front between these two places at this time. Assuming the "lake-breeze front", many phenomena of the sudden drop of air temperature as seen in other examples will be understood.

4. Summary and conclusion

The results of air temperature observations over and around the lake Inawashiro in the summer daytime can be summarized as follows:

1) Under the prevailing wind

Windward shore is cooler than the leeward shore, and the differences in temperature are about 2.8°∼4.5°C. The temperature on the lake drops with the distance from the windward shore, and a curve showing the relation between the amount of the drop and that of the distance is not linear but logarithmic. On the other hand, it is suggested that cooling effect by water surface must be studied from the view-point of latent-heat by evaporation, too.

2) Under calm weather:

The air temperature over the lake is widely homogeneous except in the inshore

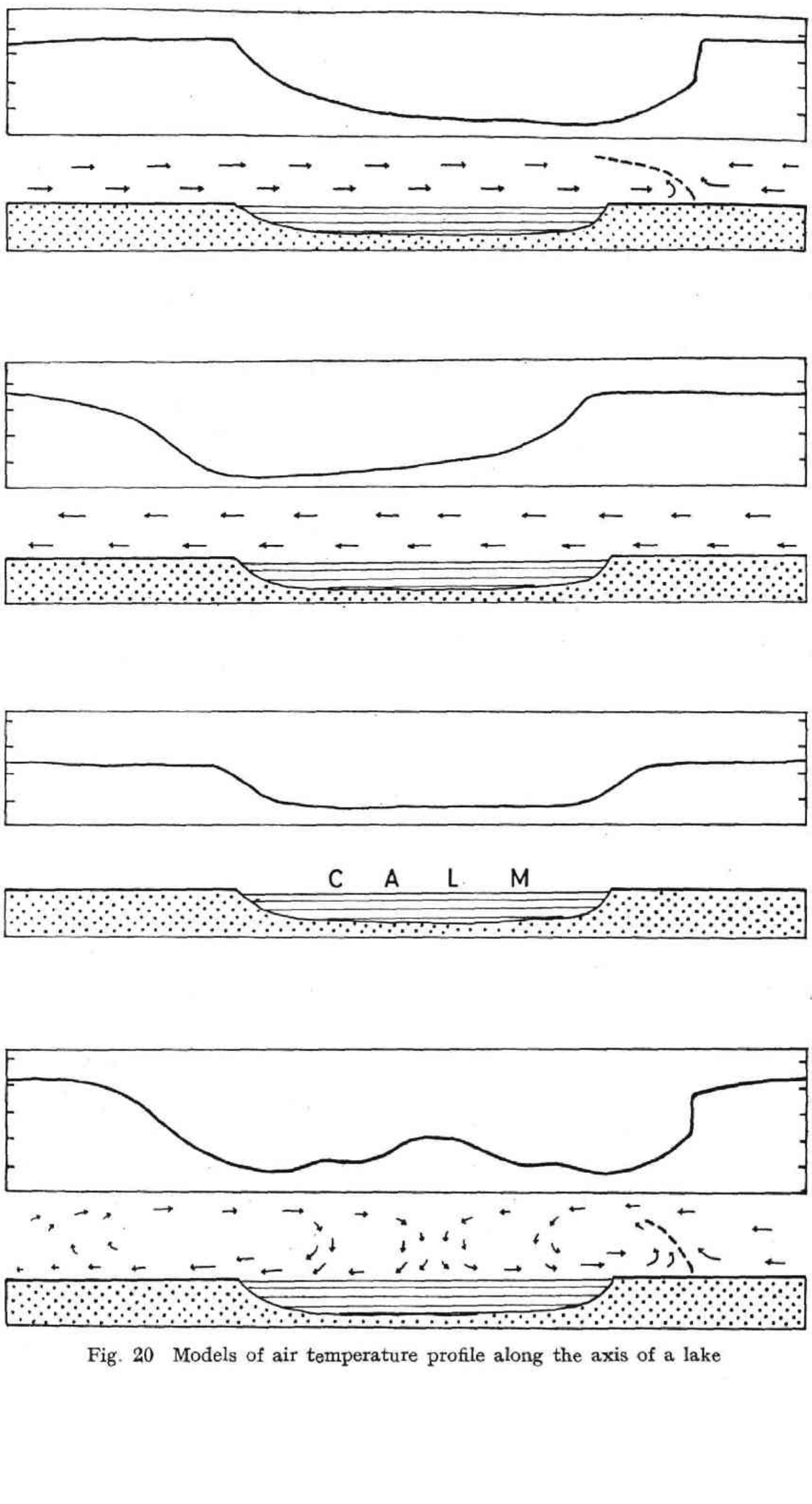

Fig. 20 Models of air temperature profile along the axis of a lake

area around the lake

3) When the lake breeze develops:

Air temperature is approximately same everywhere along the shore which is cooled similarly, being the leeside of the lake breeze. Surrounded by the inshore area thus cooled, a comparatively warm area appears over the lake center, where the ascending air is supposed to be replaced by the diverging air in the anticyclonic circulation. On the shore, a quick fall or a sudden rise in temperature is often seen at the begining of the lake breeze or when the breeze alternates with the wind from the land side. Its head is about 4°C.

4) In the plain along the lake:

Temperature gradient from the shore depend upon air-flow pattern. That is, between the shore and a place in the plain, difference in temperature is little when both of them are free from the influence of the lake, and is great when both of them are under that influence, and the greatest when the shore is under the influence while the other place is free from it. These facts suggest the existence of a lake-breeze front. Because the air layer of the lake breeze is thin, the thermal transformation of the layer seems to be completed on the whole, within the area 3.5 km from the lake shore.

5) From the above results, the models of air temperature profiles can be given as in Fig. 20.

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